RECORDS OF PRODUCTION RATE IN THE LITTLE ICE AGE OF COSMIC RAY PRODUCT ^{32}Si IN ARCTIC ICE CORES

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Abstract: Solar change, if it exists, must affect terrestrial climatic change. Recent observations of the total flux of solar radiation and the sunspot number have demonstrated the constancy of the sun. Therefore, the relation to solar change of climatic change should be investigated by using longer records.

The change of production rate of the cosmic ray products in the earth's atmosphere is known to be useful as a measure of solar activity. Then, records indicating the production rates of ^{14}C and ^{32}Si in the atmosphere were investigated, especially in the Maunder Minimum, the period 1645–1715 A.D. in which almost no sunspots are considered to have occurred.

The de Vries Peak, a prominent peak in the atmospheric ^{14}C concentration, is in remarkable agreement in sense and date with the Maunder Minimum. Nevertheless, the records indicating that the ^{32}Si production rate shows a trough in the Maunder Minimum was found in Arctic ice cores. This discrepancy found, if true, raises a doubt on the existence of the Maunder Minimum. Factors which might cause this discrepancy are discussed.

1. Introduction

Solar change, if it exists, must affect terrestrial climatic change.

Recent observations of the total flux of solar radiation and the sunspot number have demonstrated the constancy of the sun. However, this cannot absolutely prove that there is no inconstancy in the sun. Therefore, the relation to solar change of climatic change should be investigated by using longer records.

EDDY (1976) revealed the inconstancy of the sun by studying longer records. Almost no sunspots were reported to have been seen in the period 1645–1715 A.D., in the Little Ice Age; this is called the Maunder Minimum.

On the other hand, the change of production rate of cosmic ray products in the earth's atmosphere is known to be useful as a measure of solar activity. In the present study, the longer records indicating the production rates of ^{14}C and ^{32}Si, especially in the Maunder Minimum, were investigated. The de Vries Peak, a prominent peak in the atmospheric ^{14}C concentration (DE VRIES, 1958) is in remarkable agreement in sense and date with the Maunder Minimum. Nevertheless, the records indicating that the ^{32}Si production rate shows a trough in the Maunder Minimum was found in the Arctic ice cores.

The decrease in the ^{32}Si production rate is considered to be a result of the increase in solar activity. Then, factors causative of this discrepancy found in the present study will be discussed.

2. Records of Solar Change and ^{14}C Production Rate

Most recent observations of the total flux of solar radiation (the solar constant) and the sunspot number have demonstrated the constancy of the sun (STERNE and

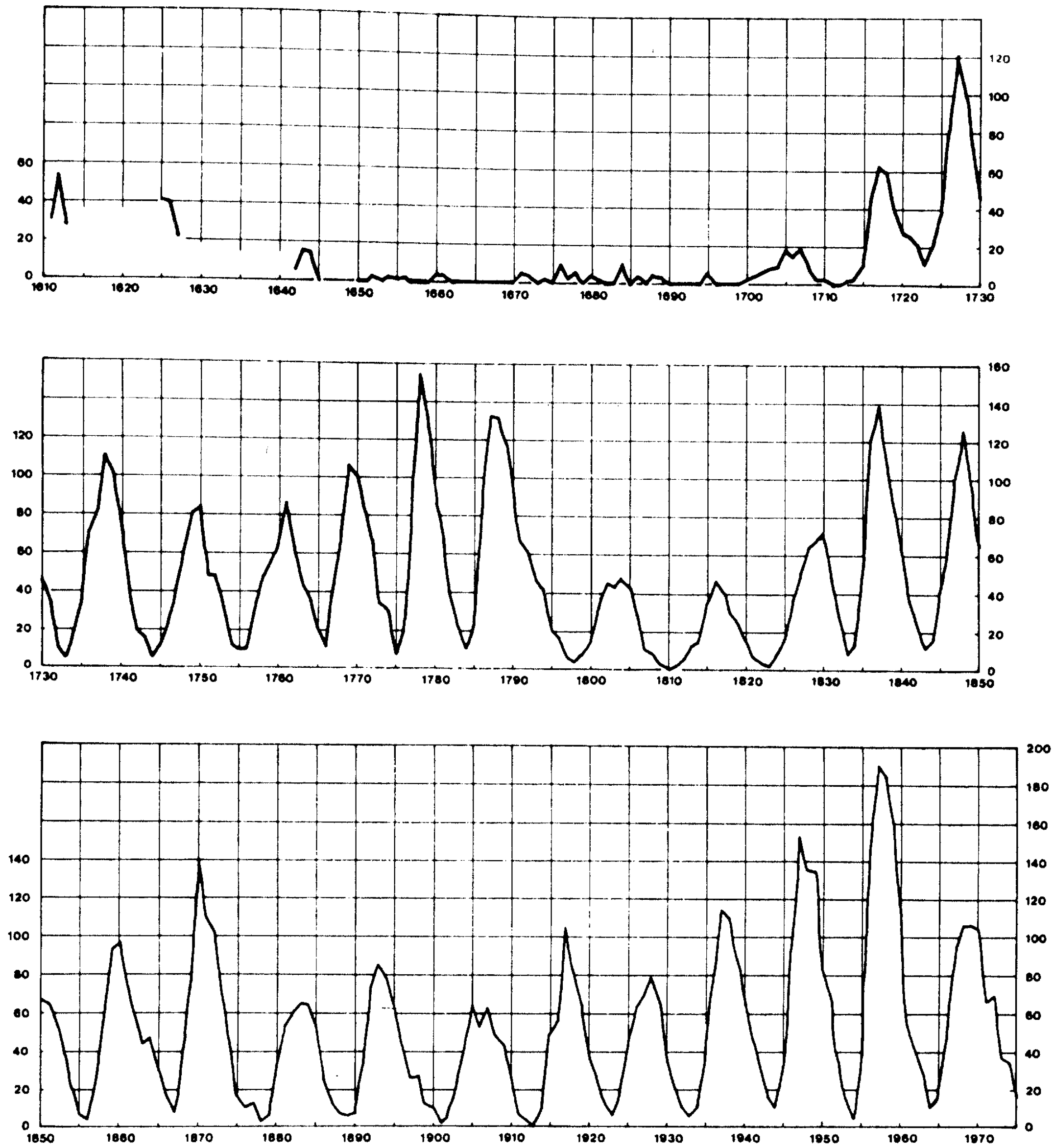

Fig. 1. Annual mean sunspot numbers in the years 1610–1975 (from EDDY, 1977).

DIETER, 1958; FRÖHLICH, 1977; EDDY, 1976, 1977). However, EDDY (1976) found an inconstancy in the sun by studying longer records.

Figure 1 shows the annual sunspot number in the years 1610–1975 (from EDDY, 1977). From this figure it is seen that almost no sunspots were seen in the period from about 1645 to 1715. This was pointed out in the 1890's by G. SPÖRER and E. M. MAUNDER (EDDY, 1976). So, EDDY (1976) called this period the Maunder Minimum.

Galileo discovered sunspots in 1610 by using the telescope invented by him. After that, sunspots were observed by amateur astronomers. In 1848, controlled observations of sunspots were organized. Therefore, the reliability of the curve in Fig. 1 is good only after 1848 and poor before 1748 (EDDY, 1976). In order to confirm the Maunder Minimum, EDDY (1976) analyzed records of naked-eye sunspot sighting, auroral records, descriptions of the eclipsed sun, and the history of atmospheric ^{14}C concentration.

The change of production rate of cosmic ray products is known to be useful as a measure of solar activity.

There exists an inverse relationship between the cosmic ray flux into the earth's atmosphere and the geomagnetic field, even if the cosmic ray intensity outside the earth's atmosphere remains constant, as pointed out by ELSASSER *et al.* (1956). There also exists on inverse relationship between the cosmic ray flux and the solar activity (sunspot cycle), as found by FORBUSH (1954). This is because, when the solar activity is high, the geomagnetic field is strengthened by the solar wind, and then some of the incoming cosmic rays (specifically, galactic cosmic rays) are prevented from reaching the earth's atmosphere. Thus, the galactic cosmic ray flux decreases while the solar cosmic ray flux increases, and the total flux decreases. Therefore, the change of production rate of the cosmic ray products is useful as a measure of solar activity.

Neutrons are produced by the cosmic rays in the earth's atmosphere. Most of the neutrons are captured by ^{14}N, yielding ^{14}C in the atmosphere. The neutron production rate varies with the same periodicity and by about the same factor (DE VRIES, 1959) as the cosmic ray flux (WINKLER, 1960; SIMPSON, 1960), during one solar cycle. So the solar change must change the production rate of ^{14}C in the atmosphere, as pointed out by STUIVER (1961). Of course, a change of the magnetic field also change the production rate of ^{14}C in the atmosphere, as found by KIGOSHI and HASEGAWA (1966).

As the records of ^{14}C concentration in the atmosphere, dendrochronologically dated tree ring samples are used. Figure 2 (from EDDY, 1977) shows relative deviations of atmospheric ^{14}C concentration from tree ring analyses for about 7500 years before the present, which are results assembled from a number of laboratories by LIN *et al.* (1975). The 1890 normal ($\Delta^{14}C=0$) is shown as a dashed, horizontal line. The relative deviation is expressed in part per thousand with positive deviation (in-

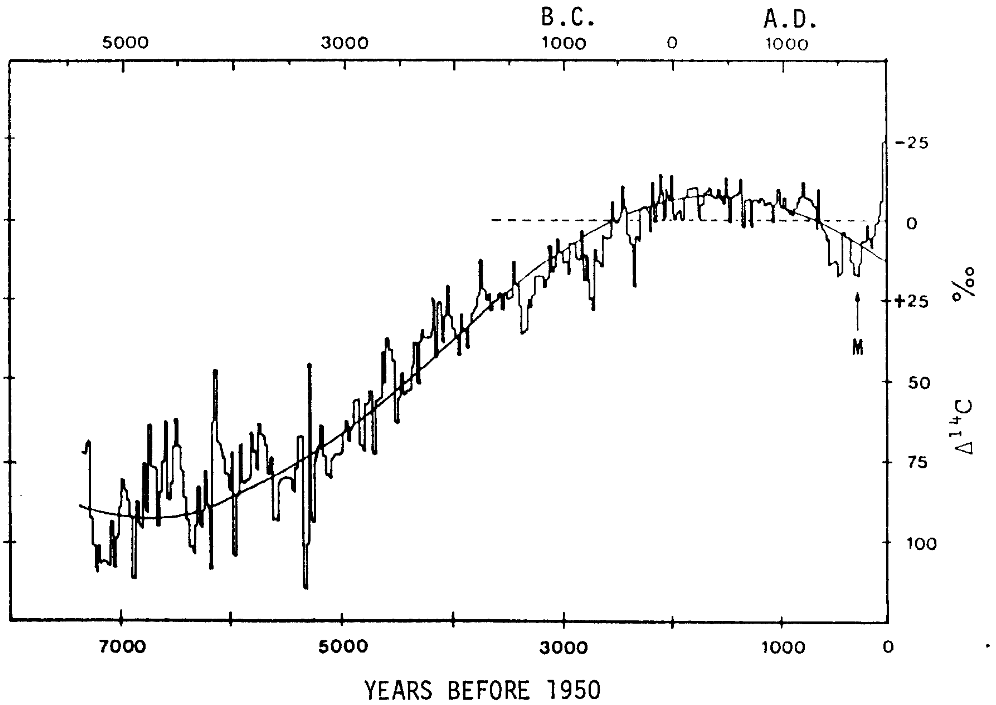

Fig. 2. *Relative deviations from the 1890 normal (dashed line) of atmospheric ^{14}C concentration for tree ring analysis for about 7500 years before the present (from* EDDY, *1977). The solid curve is a sinusoidal curve, which matches very closely the smoothed curve of changing geomagnetic field derived from paleomagnetic data. M: Maunder Minimum.*

creased ^{14}C) downward, to agree in sense with solar activity.

The observed changes of the atmospheric ^{14}C concentration show two characteristic trends, as pointed out by HOUTERMANS and SEUSS (1973). One is the long time scale trend; the remaining features with very high frequencies are superimposed on this trend. This long time scale trend is fitted with a sinusoidal curve derived from LIN *et al.* (1975), which matches very closely the smoothed curve of the changing geomagnetic field derived from paleomagnetic data. This trend can be explained by geomagnetic modulation of the cosmic ray flux. The remaining features are considered to be caused by the solar change, except for dilution of the atmospheric ^{14}C concentration recently caused by the well-known fossil fuel effect (SUESS, 1965).

The first anomaly was found in an early study (DE VRIES, 1958) of the ^{14}C record. The atmospheric ^{14}C concentration shows a marked and prolonged increase in about 1650–1720 and a prominent peak in about 1690. This de Vries Peak has been reexamined in subsequent studies, and moreover was shown to be in remarkable agreement in sense and date with the Maunder Minimum, as shown in Fig. 5 of EDDY (1976). Since then, the change of atmospheric ^{14}C concentration has been considered to be useful as a measure of production rate of the cosmic ray products, being useful as a measure of solar activity (EDDY, 1977).

3. Records of ^{32}Si Production Rate

^{32}Si is also produced by the cosmic rays in the atmosphere. As records of ^{32}Si concentration in the atmosphere, well-dated polar ice core samples are available. An ice sheet or an ice cap contains a large number of annual precipitation layers.

^{32}Si was first detected in a siliceous sponge from the coast of California by LAL *et al.* (1960). The determination of ^{32}Si requires a lot of samples. So, its determinations in polar ice cores are very few. ^{32}Si in Arctic ice cores were determined to estimate the half life of ^{32}Si (CLAUSEN, 1973) and to check a time scale determined by a theoretical ice-flow model with ^{32}Si and ^{14}C dating (PATERSON *et al.*, 1977).

Direct measurement of the half life of ^{32}Si has not been attempted because of the difficulty in determination of ^{32}Si atoms in the small samples obtainable. The estimates based on assumptions of unknown cross sections of nuclear processes leading to the formation of ^{32}Si range from 60 to 710 years (TURKEVICH and SAMUELS, 1954; GEITHOF, 1962; HONDA and LAL, 1964; JANTSCH, 1967). CLAUSEN (1973) determined the calibration curves for the well-dated cores from the Greenland ice sheet, which lead to an estimate of the half life of ^{32}Si. These cores were dated by counting the annual layers determined from seasonal cycles of oxygen isotopic composition (JOHNSEN *et al.*, 1972; DANSGAARD *et al.*, 1973; HAMMER *et al.*, 1978), and also by a theoretical ice-flow model (DANSGAARD and JOHNSEN, 1969; CLAUSEN, 1973; HAMMER *et al.*, 1978).

Figure 3 shows the specific ^{32}Si activity for about 700 years before the present in the cores from Camp Century and from Dye 3 Station, Greenland (from CLAUSEN,

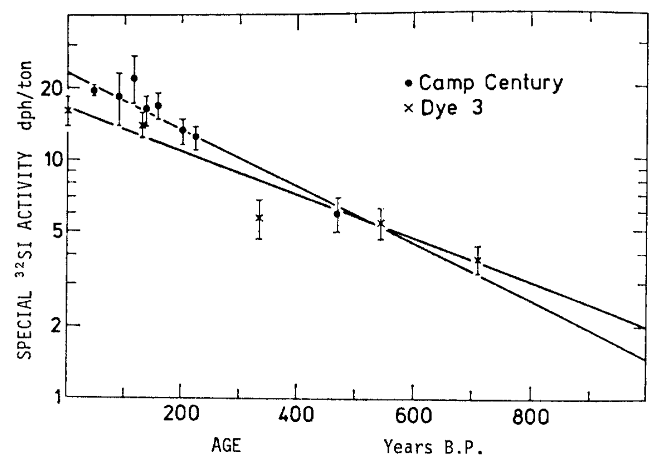

Fig. 3. Specific ^{32}Si activity for about 700 years before the present in the cores from Camp Century and from Dye 3 Station, Greenland (from CLAUSEN, 1973).

1973). The calibration curves are calculated by the method of least squares. Apparent half lives for ^{32}Si were determined from the slopes of the two lines. About 300 years was adopted as the estimate of the apparent half life of ^{32}Si. This value is now accepted as the best estimate of its half life (LAL and SOMAYAJULU, 1980).

A markedly small value is seen around 1635, though it is the only determination in the 16th and 17th centuries.

A similar ^{32}Si decrease in about the same ages is observed in adjacent cores from the Devon Island ice cap, Arctic Canada, as shown in Fig. 4 (from PATERSON *et al.*,

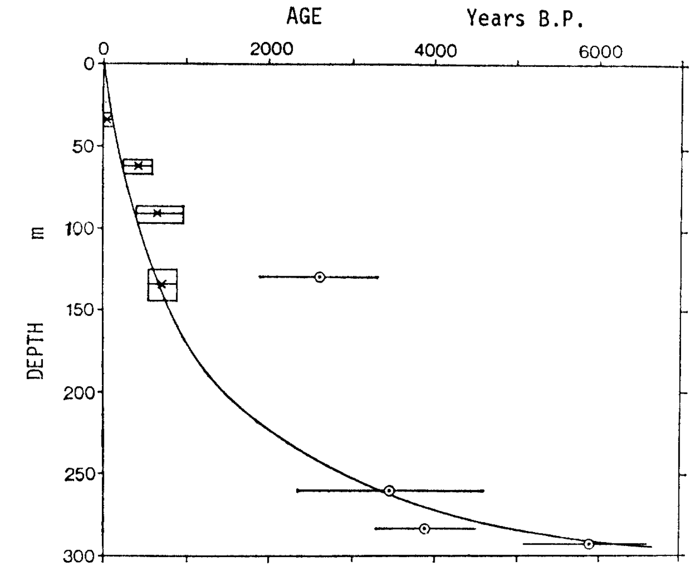

Fig. 4. Time scale (the curve) determined by a theoretical ice-flow model and absolute dates determined by ^{32}Si and ^{14}C dating in the adjacent cores from the Devon Island ice cap, Canada (from PATERSON et al., 1977). The vertical lines beside the ^{32}Si date indicate the depth interval for the ^{32}Si sample. Each ^{14}C sample covers a depth of 1.5 m. Bars show 1 standard error on each side of the mean. ×: *^{32}Si date*; ⊙: *^{14}C date.*

1977). The cores were dated by a theoretical ice-flow model and this time scale (the curve in Fig. 4) was checked with ^{32}Si and ^{14}C dating. The curve is within 1 standard error of the ^{32}Si dates and is also within 1 s.e. of two of the four ^{14}C dates and within 2 s.e. of another. The discrepancy of the youngest ^{14}C date is very large. This date is wrong. This is because the sample was contaminated by fossil CO_2, a conclusion which is supported by $\delta^{13}C$ determination. PATERSON *et al.* (1977) concluded that the curve agrees with most of the results of ^{32}Si and ^{14}C dating. However, it is obvious that the ^{32}Si concentration markedly decreases at about the same ages (the Little Ice Age) as observed in the two Greenland cores (CLAUSEN, 1973).

The results observed from the Greenland cores and the Devon Island cores indicate that the production rate of ^{32}Si also varies with time just like that of ^{14}C but shows a trough in the Maunder Minimum just against that of ^{14}C.

4. Discrepancy between Production Rates of ^{32}Si and ^{14}C in the Maunder Minimum

The change of production rate of the cosmic ray products is known to be useful as a measure of solar activity. Then, records indicating the production rates of ^{14}C and ^{32}Si in the earth's atmosphere have been investigated especially in the Maunder Minimum. Records indicating a great discrepancy between the production rates of the ^{14}C and ^{32}Si in the Maunder Minimum were unexpectedly found.

An inverse relationship must exist between the ^{32}Si concentration and the annual accumulation in the core, even if its production rate has been kept constant.

The annual layers, as previously mentioned, were determined from the seasonal cycles of oxygen isotopic composition in the Greenland cores. The annual accumulation in these cores has remained surprisingly constant after 1600 (JOHNSEN *et al.*, 1972; DANSGAARD *et al.*, 1973). Therefore, the low ^{32}Si concentration around 1635 found in the Dye 3 Station core (Fig. 3) was not caused by the change of annual accumulation.

In the Devon Island cores, the time scale determined by the theoretical ice-flow model agrees with most of the results of ^{32}Si and ^{14}C dating. Therefore, the assumption that the annual accumulation had been constant during the core formation was concluded to be reasonable. The decrease in the ^{32}Si concentration in the Maunder Minimum was not caused by an increase in the annual accumulation in the Devon Island cores, too.

The deposition of ^{32}Si produced in the earth's atmosphere on the earth's surface is a one-way process, whereas the atmospheric ^{14}C concentration on the earth's surface is affected by the CO_2 circulation among the atmosphere, the hydrosphere and the biosphere. Therefore, the atmospheric ^{14}C concentration must be affected by climatic change.

LINGENFELTER (1963) calculated the change of ^{14}C production rate due to modulation of the incident cosmic ray flux by the sunspot number. As STUIVER (1961) and HOUTERMANS and SUESS (1973) had calculated according to Lingenfelter's formula, the change of ^{14}C production rate is to small to produce the de Vries Peak of atmospheric ^{14}C concentration. According to a recent calculation by KIGOSHI (1979), the change of ^{14}C production rate after the Maunder Minimum is estimated to produce at most one-third of the observed decrease of atmospheric ^{14}C concentration.

As summarized by KIGOSHI (1979), the influence of climate on atmospheric ^{14}C concentration has been discussed in many studies. The correlation between the climate and observed atmospheric ^{14}C concentration on the dated tree rings has been shown. The influence of climate on the transfer rate of CO_2 between the atmosphere and the hydrosphere has been studied. Most recently, KIGOSHI (1979) pointed out that the estimated influence of climate on atmospheric ^{14}C concentration is 3–5 times greater than the direct contribution of the change of ^{14}C production rate at the end of the Maunder Minimum.

The transfer processes of CO_2 among the atmosphere, the hydrosphere and the biosphere are now considered to be too complicated to estimate completely the influence of climate on the atmospheric ^{14}C concentration. Therefore, the change of atmospheric ^{14}C concentration may not always reflect that of the ^{14}C production rate in the atmosphere. Alternatively, the change of ^{32}Si concentration in the ice cores is considered to reflect that of the ^{32}Si production rate in the atmosphere. Since the decrease in the ^{32}Si production rate results from the increase in solar activity, the decrease in ^{32}Si concentration found around 300 years ago in the ice cores, if true, is incompatible with the Maunder Minimum. The ^{32}Si profile is being determined in the core which was obtained in 1974 by the 15th Japanese Antarctic Research Expedition from Mizuho Station, East Antarctica. Further determinations of ^{10}Be and ^{36}Cl profiles in the ice cores are desired to check the discrepancy found.

The production processes by cosmic rays of ^{32}Si and ^{14}C are different. ^{14}C is produced through the capture by ^{14}N of neutrons, which are produced by cosmic rays. On the other hand, ^{32}Si is produced by spallation of ^{40}Ar by cosmic rays. Therefore, if ^{14}C is produced mainly by galactic cosmic rays and ^{32}Si is produced mainly by solar cosmic rays, the discrepancy found in the present study may be clearly explained.

To solve this discrepancy is considered to be essential to progress in the studies of climatic change related to solar change and to require the assistance of scientists working on solar activity, cosmic rays, cosmic ray products, CO_2 circulation and so on.

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